

Exploiting Combination Techniques in Random Access MAC Protocols: Enhanced Contention Resolution ALOHA

Federico Clazzer, *Student Member, IEEE*, Christian Kissling,
and Mario Marchese, *Senior Member, IEEE*

Abstract

Recently, random access (RA) protocols have acquired new interest from the scientific community not only in satellite communication scenarios but also due to the opening of new fields as smart grid and machine-to-machine (M2M) applications. Unslotted ALOHA-like RA protocols are very attractive for such applications thanks to the low complexity transmitters and to their complete avoidance of synchronization requirements. Evolutions of the ALOHA protocol employ time diversity through proactive replication of the packets but this diversity is not fully exploited at the receiver. The novel RA protocol named enhanced contention resolution ALOHA (ECRA) is presented, which goes beyond the limitation introducing combination techniques in the receiver algorithm. The behaviour of ECRA is investigated through mathematical analysis and simulations for two combination techniques, selection combining (SC) and maximal-ratio combining (MRC). Approximations of the packet error rate (PER) for unslotted RA protocols, including ECRA, well suited for the low channel load regime is also presented. Furthermore, ECRA and recently presented RA protocols, are analyzed in terms of different metrics, including spectral efficiency, showing that ECRA is able to largely outperform both slotted and unslotted schemes.

Part of the material in this paper was presented at the 2013 International ITG Conference on Systems, Communications and Coding (SCC).

This work is a first draft and is currently under finalization for a journal submission.

Federico Clazzer is with the Institute of Communication and Navigation (Satellite Networks Department) of the German Aerospace Center (DLR), Muenchener Str. 20, 82234 Wessling, Germany. E-mail: Federico.Clazzer@dlr.de.

Christian Kissling is with Triagnosys Gmbh - Zodiac Aerospace, Argelsrieder Feld 22, 82234, Wessling, Germany. E-mail: christian.kissling@triagnosys.com.

Mario Marchese is with the Department of Electrical, Electronic, and Telecommunications Engineering, and Naval Architecture (DITEN), Via Opera Pia 13, 16145 Genova, Italy. E-mail: Mario.Marchese@unige.it.

Index Terms

Medium access control, random access, ALOHA, successive interference cancellation, selection combining, maximal-ratio combining.

I. INTRODUCTION

For multiple-access wireless communication systems that are dynamic in terms of resource requests from the transmitting nodes, fixed allocation is normally inefficient and dynamical resource allocation, e.g. demand assigned multiple access (DAMA), can be beneficial [1]. However, there are a number of scenarios where DAMA is unable to counteract efficiently the dynamics of the resource requests. As examples we can mention all the cases where the channel traffic of the transmitters shows a bursty and unpredictable nature, when there is a very high number of transmitters and coordination is hard to achieve, or when delay-critical applications are considered. The last case is of particular importance in geostationary orbit (GEO) satellite communication systems. In such a scenario, before the resource request of a given transmitter can be satisfied, an additional delay of 1 round trip time (RTT) of ca. 500 ms may elapse. Such additional delay can be critical for several applications [2].

Random access (RA) protocols have evolved significantly from the original idea of ALOHA proposed by Abramson in 1970 [3] and its slotted evolution [4], [5]. Recently, driven by a number of application scenarios like underwater networks [6], RFID communication systems [7], vehicular ad hoc networks [8], machine-to-machine (M2M) communication systems [9] and satellite networks [10], many new random access (RA) schemes have been proposed.

Among them, one of the most promising is contention resolution diversity slotted ALOHA (CRDSA) [11]. CRDSA is an evolution of diversity slotted ALOHA (DSA) [12]. DSA provides a lower delay and higher throughput with respect to slotted ALOHA (SA) under very moderate channel traffic conditions, by transmitting proactively two or more times the same packet. The packet instances (replicas in the following) are sent separately with a random delay. The throughput difference between SA and DSA is limited especially for moderate to heavy channel traffic conditions. In DSA a tradeoff between time diversity introduced by the presence of replicas, and channel traffic increase, arises. When the channel traffic is limited, the replication of packets is beneficial because the collision probability remains relatively low, while the probability that one replica is received collision-free is high. At moderate channel traffic instead, the

replication of packets will harm the performance because the collision probability will increase so much that the benefit of time diversity is lost.

A larger gain is achieved when both time diversity and successive interference cancellation (SIC) are exploited. CRDSA follows the idea of DSA to send more than one packet replica per user and introduces SIC at the receiver to improve the throughput. In CRDSA, transmission is organized into frames, where a user is allowed to transmit only once. The user replicates its packet two times and places the identical replicas in uniformly random selected slots, providing in both replicas the information of the selected slots. At the receiver, SIC exploits the presence of multiple replicas per frame for clearing up collisions. Every time a packet is decoded, SIC is able to reconstruct the waveform and to subtract it where the replicas are sent in the frame thanks to the information on the selected slots. This can possibly remove their interference contribution with respect to other packets. The performance evaluations in [11] have shown that the maximum throughput of CRDSA can be impressively extended from $S \cong 0.36$ (the peak throughput of SA measured in average number of successful transmissions per transmission period [13]¹), up to $S \cong 0.55$. Further throughput improvements can be achieved when, i) more than two replicas per user and per frame are sent, ii) received power unbalance and capture effect are considered [14]. Stability investigations of CRDSA have been performed in [15], while more recently an analytical framework for slotted RA protocols embracing SA, DSA and CRDSA has been presented in [14]. Irregular repetition slotted ALOHA (IRSA) [16] is an extension of CRDSA, where the number of replicas sent by the users is drawn from a probability distribution optimized for maximizing the throughput. The bipartite-graph representation is introduced and exploited for characterizing the interference cancellation (IC) process, helping the optimization procedure. An extension of irregular repetition slotted ALOHA (IRSA), named coded slotted ALOHA (CSA) has been presented and analysed in [17], where the packets are not simply repeated as in IRSA and CRDSA, but instead, they are encoded. IRSA approaches a theoretical throughput of $S = 0.97$ with a distribution containing a maximum of 16 replicas per user obtained via differential evolution [16]. Both IRSA and CSA are able to achieve a throughput arbitrarily close to 1 [18], for arbitrarily long frames and letting the number of replicas goes

¹Following the definition of [13] we assume that a transmission period is equal to T_p seconds, which coincides with the physical layer packet duration and also coincides with the slot duration. Therefore, for slotted protocols the throughput can be measured also in packets/slot.

to infinity. In [9], [19] instead, a frameless ALOHA protocol is proposed. The key concept is to adaptively increase the number of slots per frame until a target number of users is correctly received, adopting an analogy with rateless codes.

Relevant for the present work is the idea proposed by the authors in [20] to adopt an iterative decoding procedure in order to counteract the hidden terminal problem in the IEEE 802.11 medium access (MAC) protocol. The authors observe that packets colliding once are very likely to collide again in retransmissions. However, the jitter may differ in the two collisions and can be exploited for triggering a decoding procedure that identifies portions of the packets free from interference, and proceeds eliminating the demodulated portion into the other collision. This can free from interference a section of the second packet collided, that can be now decoded and removed from the first collision. Iterating the procedure can possibly lead to decode both packets. Extension to this approach are proposed in [21] where instead of the hard-decoded symbols, soft-information is propagated.

Similarly to CRDSA, the recently proposed contention resolution ALOHA (CRA) [2] brings to the unslotted RA protocols the SIC procedure into the receivers, enhancing the protocol performance. A more detailed review of this protocol can be found in Section IV-A. Similarly to CRA, the asynchronous contention resolution diversity ALOHA (ACRDA) exploits concepts borrowed from CRDSA in an unslotted and unframed scenario [22]. In unslotted RA protocols, the peculiar relaxation of synchronization requirements is very useful for low cost and low complexity transmitter applications. However, CRA does not exploit the inherent time diversity of the interference among packets which naturally arises due to the asynchronous nature of the protocol, i.e. different portion of the replicas of a given user can be interfered.

In contrast, enhanced contention resolution ALOHA (ECRA), the focus of this work, takes advantage of this effect and improves the performance of the unslotted schemes. The objective of the paper is to analyze numerically and analytically the performance of the ECRA decoding algorithm, and the main contributions of the present work can be summarized as:

- *Extension of RA protocols towards packet combination techniques* such as selection combining (SC) and maximal-ratio combining (MRC) [23], [24]. The novel ECRA exploits the time diversity of the interference pattern suffered by the replicas for creating a combined packet at the receiver on which decoding is attempted. This procedure is able to enhance the SIC procedure and to increase the performance with respect to CRA.
- *Development of an analytical approximation of the packet error rate (PER) performance*

particularly tight for low offered channel traffic. This approximation is derived starting with the analysis of the collision patterns unresolvable with SIC. The PER approximation is derived first for slotted protocols² and then extended to the unslotted ones, both for CRA without and with forward error correction (FEC) as well as for ECRA.

- *Comparison of RA slotted and unslotted protocols with several metrics* as throughput, spectral efficiency and normalized capacity, in order to identify scenarios where unslotted protocols are able to outperform slotted ones.

II. PRELIMINARIES

We consider MAC frames with a duration of T_f seconds where N_u users attempt transmission. Each user has a packet composed by L_s symbols each of duration T_s seconds, to transmit. We denote with $T_p = T_s \cdot L_s$ the packet transmission period³ in seconds and with L_b the number of information bits inside each of the users' packets. The code rate R is defined as $R = L_b/L_s$. In general, for unslotted schemes the frame structure is artificial and can be completely removed [25]. In fact, the pointer field can indicate the relative time offset of the other replica instead of the slot as proposed for CRDSA. Following the framework initiated in [2] where CRA has been proposed, in the rest of the paper a frame structure is maintained.

At the beginning of a MAC frame, each of the N_u users selects d time instants where d identical replicas of its packet will be transmitted. We refer next to d as the repetition degree of the packet. The time instants are drawn from a uniform distribution with the only constraint of avoiding interference between replicas of the same user. The information on the replicas position is stored in a dedicated portion of the replicas header. We assume that the single data packet replicated d times within the frame can be either a new packet or the retransmission of a previously collided packet. Moreover, retransmission of collided packets cannot be initiated in the same MAC frame where the collisions happened. In this way, N_u takes into account of both new transmissions and retransmissions. Notice that, under this assumption and the finite user population assumption, the system is always stable. The offered channel traffic G is given by $G = \frac{N_u \cdot T_p}{T_f}$, measured in number of packet transmission attempted per T_p seconds. Since the users replicate their packets d times, the physical offered traffic is increased d times w.r.t. G .

²It has to be noted that a similar result only for slotted protocols has been derived in [14].

³ T_p is the transmission period resulting after the channel encoding and modulation. Therefore, this is the effective duration of physical layer the packets.

The expression of G can be thought as the *logical traffic* because it measures the transmission attempts normalized to the packet duration, and it is not influenced by the number of replicas. In this way, it is equivalent to the offered channel traffic of protocols like ALOHA or SA where there are no replicas. Furthermore, we assume an additive white gaussian noise (AWGN) channel without fading.

Consider one replica for the u -th user. We denote the associated transmitted signal as $\mathbf{x}_u(t)$. The sampled received signal (for the s -th symbol in the packet) is modelled as

$$y_{s,u} = x_{s,u} + i_{s,u} + n_{s,u}$$

where $i_{s,u}$ is the interference contribution and $n_{s,u} \sim \mathcal{N}(0, \sigma_n^2)$ is modelled as a Gaussian random variable accounting for the noise contribution. The signal to interference and noise ratio (SINR) observed for the s -th symbol within the packet of user u is then

$$\gamma_{s,u} = \frac{P}{N + I}, \quad (1)$$

where $P = \mathbb{E}[|x_{s,u}|^2]$, $N = \sigma_n^2$ and I is the average interference power, $I = \mathbb{E}[|i_{s,u}|^2]$. The interference power is heavily time varying for unslotted schemes, due to the potential different number of interferes for each symbol. The signal-to-noise ratio (SNR) Γ for the s -th symbol within the packet of user u is finally

$$\Gamma_{s,u} = \frac{P}{N}.$$

Before moving to review the decoding procedure of CRA and analyze the one of ECRA, we will review typical channel models used for evaluating RA protocols.

III. COLLISION CHANNEL MODELS

In this Section, two collision channel models will be presented. The destructive collision model, is the one typically used for evaluating the performance of RA protocols and has been exploited in the ALOHA original paper [3]. The threshold based model instead, comes into play when packets are protected with FEC and the interference is not always destructive or also when packet combination is applied before decoding.

A. Destructive Collision Model

The destructive collision channel model, called also collision model [26], is an abstraction of the physical layer that allows only collision free packets to be correctly received. Under this assumption, every time a collision occurs, all the involved packets are lost. This model has been assumed in the early works on RA [3] as well as in the investigation of recent slotted RA protocols [11], [16].

Thanks to its simplicity, the destructive collision model is well suited for extracting the MAC performance and for analytical evaluations but lacks of accuracy when it comes to investigate the MAC protocol in realistic scenarios. In particular, spatial diversity, geometry and transmitters characteristics may differ introducing diversity in the received signal power. This diversity allows potentially to *capture* strong signals i.e., correctly decode packets also in presence of collisions. This effect has been investigated already in [4] for SA and in [14] for recent slotted RA protocols. Furthermore, when FEC is introduced, a certain interference level can be tolerated before packets are lost due to collisions. This is especially beneficial in unslotted RA protocols where the interference level highly differs due to the random arrival times of the packets, at the receiver. For these reasons, the threshold based model is presented next.

B. Threshold Based Model

The threshold based model permits to investigate a MAC layer with a more sophisticated physical layer, where features like FEC, multi-packet reception and capture effect can be taken into consideration [27], [28]. The threshold is used to discriminate between decodable and not-decodable packets and is normally defined in terms of SINR.

Since we are dealing with unslotted protocols, our threshold will have a slightly modified form, due to the presence of potentially different levels of interference on each packet symbol. We assume that, although user packets have finite length, a threshold based model relying on channel capacity can be used to model the conditions under which, decoding of a packet succeeds. To this aim, we first introduce the channel capacity as

$$C_{u,r} = \frac{1}{L_s} \sum_{s=1}^{L_s} \log_2 (1 + \gamma_{s,u,r}), \quad \text{bits/channel use}$$

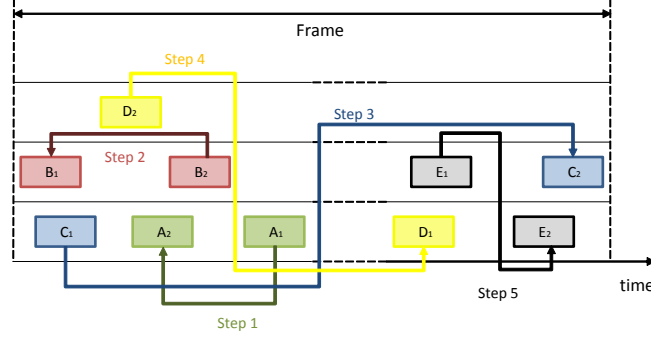


Fig. 1. SIC procedure in CRA.

where $\gamma_{s,u,r}$ is the SINR perceived by the s -th symbol of the r -th replica of user u , while $C_{u,r}$ is the capacity of the r -th replica of user u . Assuming capacity achieving codes, the successful decoding condition is then

$$R_{u,r} \leq C_{u,r},$$

where $R_{u,r}$ is the rate selected for the replica r of user u . In the following we will assume the same rate for all users and replicas, i.e. $R = R_{u,r}$ for $u = 1, \dots, N_u$ and $r = 1, \dots, d$. We can also note that the destructive collision model is a special case of the threshold based model, where the rate R chosen allows only packets without collision to be successfully decoded.

IV. UNSLOTTED RA DECODING ALGORITHMS

In this Section we will first review the decoding algorithm used in CRA before moving to the novel ECRA decoding algorithm.

A. CRA Decoding Algorithm

As mentioned in Section II, in CRA each user sends d identical replicas starting at d uniformly random distributed times within the frame. The CRA decoding algorithm exploits the SIC procedure for enhancing the performance and for resolving possible collisions. In order to clarify the SIC procedure of CRA, a representative received frame is shown in Fig. 1, where the degree is $d = 2$. The packets are placed on different levels only for simplifying the visualization, but they are assumed to be sent in the same frequency and therefore they are partially overlapping in the frame; the two replicas of each user are denoted with the same capital letter and indexes

1 and 2 respectively. Under the assumption of destructive collision channel model, the SIC will succeed in decoding the first packet free from interference, i.e. packet A_1 . Once it is successfully decoded the corresponding waveform can be replicated and subtracted in the position of its twin replica, packet A_2 . In this way, the collision with packet B_2 can be resolved allowing its correct decoding and both interference contributions of packets B_1 and B_2 can be removed from the frame. In this scenario, the SIC procedure is iterated on the other packets until all of them can be successfully decoded.

As opposed to CRDSA, in CRA no time division in slots is present in the frame and thus the replicas of the users can be placed within the frame without constraints, except that replicas of one user must not interfere with each other. CRA is able to reach a maximum throughput of $S \cong 0.28$ for two replicas per user and per frame [2].

From a practical perspective, FEC in CRA is beneficial (beyond providing robustness with respect to channel noise) also when no power unbalance among users is present, unlike in CRDSA where packets can be either fully interfered or interference free. In CRA, packets partially colliding in fact, are more probable than packets completely interfered and when FEC is introduced, the throughput can be further enhanced exceeding 0.28 [2], [29].

B. ECRA Decoding Algorithm - Combining Techniques with RA

In ECRA, as in CRA, each user sends d identical replicas starting at d uniformly random distributed times within the frame. Additionally, ECRA follows a two-steps procedure for decoding the packets at the receiver side. In the first step, the SIC procedure is applied similarly to CRA. Nevertheless, there are scenarios where not all the collision patterns⁴ can be resolved, for example Fig. 3(b), and in these cases the second step introduced with ECRA can boost the receiver performance.

In ECRA's second step, packet combining techniques are applied on the non-decoded packets which are remaining after the first step, and on these *combined packets* decoding is attempted.

Definition 1 (Combined packet). A packet composed by symbols belonging to at least two replicas of the same user is denoted as *combined packet*. Combined packets can be composed by sets of symbols belonging to different replicas or can have symbols being a weighted sum of the symbols coming from different replicas.

⁴More details on the collision patterns unresolvable with SIC can be found in Section V.

When the decoding is successful, the replicas contribution is removed from the frame, enabling a second set of SIC iterations. The way how the combined packet is created depends on the combining technique and has an impact on the decoding performance. Two combining techniques are presented next, SC and MRC.

1) *ECRA selection combining (ECRA-SC)*: The first combination technique applied in ECRA's second step is selection combining [23], [24]. In particular, ECRA-SC creates a combined packet for each user remaining in the frame after the first step. The combined packet is composed by the replicas sections with the highest SINR, symbol by symbol. After recombination, decoding is attempted on the combined packet. If the decoding is successful, the packet is re-encoded, modulated and its interference contribution is removed in all the positions within the frame where the replicas are placed. Like in the first step, the mentioned procedure is iterated until no more packets can be successfully decoded.

Given $\gamma_{s,u,r}$ from equation (1), for each replica r of user u replicas, the ECRA-SC decoding algorithm selects the s -th symbol with the highest SINR, $\gamma_{s,u}^{\text{SC}}$, among all symbols in the same location within these replicas, i.e.,

$$\gamma_{s,u}^{\text{SC}} = \max_r \{\gamma_{s,u,r}\} \quad \text{for } r = 1, \dots, d. \quad (2)$$

Obviously, since equation (2) is valid for all the symbols in a packet, we can immediately conclude that the SINR over the entire combined packet created by ECRA-SC for the generic user u , is always greater than or equal to the SINR of all the replicas of that user.

2) *ECRA maximal ratio combining (ECRA-MRC)*: The second combination technique applied in ECRA's second step is maximal-ratio combining [24]. For MRC the SINR under independent interference assumption is the sum of the d signals SINRs, i.e.

$$\gamma_{s,u}^{\text{MRC}} = \sum_{k=1}^d \gamma_{s,u,r}.$$

When the decoding on the combined packet is successful, the packet is re-encoded, modulated and its interference contribution is removed from all the positions within the frame where the replicas were placed. Also here, the procedure is iterated until no more packets can be successfully decoded.

ECRA-MRC is clearly able to improve the performance w.r.t. ECRA-SC, being $\gamma_{s,u}^{\text{MRC}} \geq \gamma_{s,u}^{\text{SC}}$.

3) *Summary and Comments:* The scenarios under consideration in the work of [20] and its extension [21], are similar to the one that can block the SIC procedure, as for example in Fig. 3(b), although some differences in the solutions between their work and ECRA can be identified. ECRA creates the combined packet and tries decoding on it, while [20] requires an iterative demodulation procedure within packet portions, that may increase the overall packet decoding delay. Furthermore, in [20] an error in one decoded bit propagates to the entire packet unless compensated by further errors. This is due to the iterative procedure applied which subtracts the uncorrect bit from the same packet in the second collision, while in ECRA an error in one decoded bit will not affect any other portion of the packet. Finally, MRC is not foreseen for the case addressed in [20] and in [21]. In the comparison between ECRA and [21], beyond the already presented differences with [20] also practical implementations issues arise, e.g. how to access the soft information.

The second step of ECRA needs complete knowledge of the replicas position of the remaining users in the frame, regardless the combining technique used. Pointers stored in the header, in the form of pseudo-random seed, can be used for retrieving information on the replicas locations. This option was proposed first in [11] for slotted protocols, but can be extended also to ECRA. In [30] the optimum header position for systems employing SIC is investigated and it was shown that in the low to moderate channel traffic regime, low probability of interference in the header can be found, while for high channel traffic regimes, replicating the header twice can be beneficial. Moreover, if dedicated FEC is introduced for protecting the header, lower header loss probability can be expected⁵.

MRC combining technique requires the knowledge of the SINR symbol-by-symbol, in order to choose the best weights [23] beforehand the combination is done. In case this information cannot be retrieved, combining can be applied with equal weights for all the symbols, i.e. equal gain combining (EGC).

In Fig. 2, the simulated cumulative distribution function (CDF) of the symbols' SINR for CRA, ECRA-SC and ECRA-MRC is shown for an offered channel traffic $G = 1$ and $\Gamma = 10$ dB (equal for all the users). For both ECRA-SC and ECRA-MRC the symbol SINR considered for the CDF is the one after the combiner. The CDFs for both combining techniques show remarkable

⁵Very robust FEC applied to the headers can allow retrieving the information about replica locations although the packet itself is not decodable due to collisions.

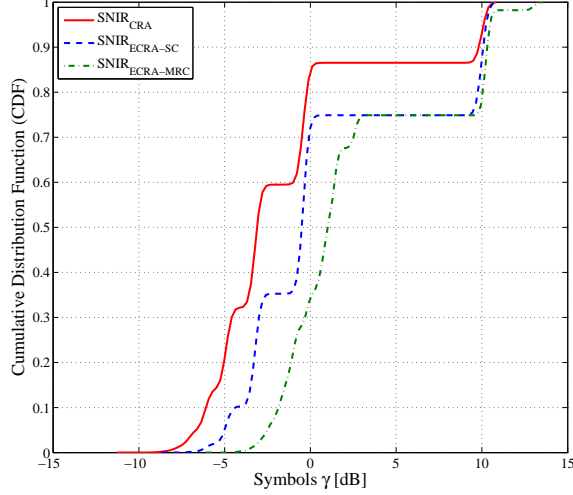


Fig. 2. CDF of the symbols SINR for CRA, ECRA-SC and ECRA-MRC for $G = 1$ and $\Gamma = 10$ dB.

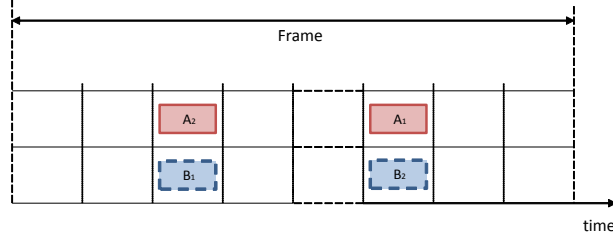
SINR gains w.r.t. the SINR prior to combination. Moreover, for low SINR, MRC shows a further remarkable gain over SC. In the next Section, approximations for the PER particularly tight for the low offered channel traffic are presented.

V. PERFORMANCE AT LOW ERROR PROBABILITIES

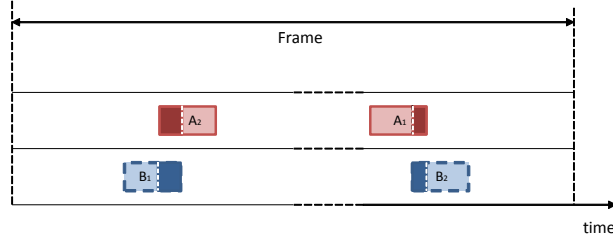
Before moving to the analytical derivation of the approximation for the PER, some preliminary definitions are required. In both slotted and unslotted schemes SIC is unable to recover packets from particular interference patterns. Assuming for example, the destructive collision channel model, and if all the d replicas of two users are interfering each other, the packets sent by the users are all lost. We refer to such configurations as *loops*.

Definition 2 (Loop). A *loop* is a subset of users such that the collision pattern given by their replicas does not leave any replica interference free. (Under the assumption of destructive collisions, none of the users in the loop can be successfully decoded.)

In Fig. 3(a) the simplest loop that can occur in case of CRDSA is shown. In this scenario both replicas of the two users cannot be decoded because every replica is fully interfered by one replica of the other user. Similarly, in case of CRA shown in Fig. 3(b), under the same assumption of destructive collision, the packets of both users are undecodable. This consequence in general



(a) CRDSA loop



(b) CRA loop and UCP

Fig. 3. CRDSA and CRA loops of two users with $d = 2$, where for CRA the loop is also an UCP. The first user sends replicas A_1 and A_2 while the second user sends replicas B_1 and B_2 . For CRDSA, the SIC procedure is not able to decode any of the two packets in none of the two slots. Also in the CRA case the resulting UCP cannot be resolved and the SIC procedure is blocked. However, since different portions of the two replicas collide a proper recombination of packet fragments (as applied by ECRA) may allow decoding the user packets.

holds when no FEC is used to protect the packets. Conversely, when FEC is exploited the collision might be resolvable, leading to the following definition.

Definition 3 (Unresolvable collision pattern). An *unresolvable collision pattern (UCP)* is a loop where, even in presence of FEC, no user in the set can be successfully decoded.

In this way, every UCP is also a loop, but not viceversa. The viceversa holds only if destructive collisions are assumed, i.e. no FEC. In order to evaluate the probability of UCP, a generalization of the definition of vulnerable period [13] is required.

Definition 4 (Vulnerable period). Given the transmission of a packet in the MAC frame between time t_0 and $t_0 + T_p$, the *vulnerable period* of this packet is the interval of time $[t_1 \leq t_0 \leq t_2]$ in which the start of any other transmission can cause an UCP. Assuming destructive collisions, $t_1 = t_0$ and $t_2 = t_0 + T_p$ for slotted schemes, while $t_1 = t_0 - T_p$ and $t_2 = t_0 + T_p$ for unslotted ones. Instead, when FEC is introduced $t_1 > t_0 - T_p$ and $t_2 < t_0 + T_p$ for unslotted schemes.

Assuming no FEC, the duration of packets' vulnerable period is doubled in unslotted schemes

w.r.t. comparable slotted ones [13]. In this way, both probability of loops and probability of UCP are greater for the former protocols. Nevertheless, in the configuration reported in Fig. 3(b), different packet sections of the two replicas are affected by interference. Assuming that the second, not collided, portion of packet A_2 is combined with the first, not collided, portion of packet A_1 , and decoding is attempted on this combined packet, the packet of the first user can be correctly decoded. In this way, the UCP can be resolved and also the packet of the second user can be correctly decoded. In the next Subsection we will analytically evaluate different lower bounds on the UCP, while after we will move from the lower bounds on the UCP to the approximation of the PER.

A. Lower Bounds on Average Number of UCP

We would like to analytically evaluate the average number of UCPs in finite length MAC frames. While the probability of having an UCP decreases with increasing frame length, practical frame lengths have a non negligible probability of UCPs [16]. The analysis is performed for a generic degree d and for UCPs involving two users, therefore it is a lower bound.⁶ We first derive the expression for the case of slotted schemes e.g., CRDSA, and then we extend it for the unslotted case e.g., CRA and ECRA, under the destructive collision assumption. Secondly we also investigate the case with FEC for CRA as well as for ECRA-MRC.

1) *Slotted Case:* For this case we need to introduce a further quantity; the number of slots N_S which compose each MAC frame. Given the transmission of the first user in one of the N_S slots, the probability that the second user selects the same slot is $1/N_S$. In case of generic degree d an UCP involving the two users happens only if all the $2 \cdot d$ replicas are sent in the same d slots two by two. Called pairwise collision probability $\Pr\{U_1 \odot U_2\}$ the probability that two users sending d replicas are involved in an UCP, it holds

$$\Pr\{U_1 \odot U_2\} = \frac{1}{\binom{N_S}{d}}. \quad (3)$$

In a MAC frame N_u users are transmitting d replicas each. Therefore, the average number of UCPs $\mathbb{E}[L^{SL}]$ involving two users is given by

⁶The average number of UCPs is greater than the lower bound analytically derived here, because there are also UCPs involving more than two users.

$$\mathbb{E}[L^{\text{SL}}] = \binom{N_u}{2} \cdot \Pr\{U_1 \odot U_2\} = \frac{\binom{N_u}{2}}{\binom{N_S}{d}}, \quad (4)$$

where $\binom{N_u}{2}$ is the combination of the N_u user transmitting in a MAC frame taken two by two.

2) *Unslotted Case*: The probability of interference among two user transmitting in a MAC frame in case of an unslotted RA scheme, is given by the ratio between the length of the vulnerable period $2 \cdot T_p$, and the length of the frame T_f , i.e. $(2 \cdot T_p)/T_f$ ⁷. In case of generic degree d an UCP involving the two users happens only if d replicas are sent in the vulnerable periods of the remaining other d replicas. In this case, the pairwise collision probability $\Pr\{U_1 \odot U_2\}$ is

$$\Pr\{U_1 \odot U_2\} = \frac{1}{\binom{\overline{N}_S}{d}},$$

where the only difference with equation (3) is in the term \overline{N}_S , which is defined as $\overline{N}_S = \lfloor T_f/(2 \cdot T_p) \rfloor$. Since in practical cases $T_p \ll T_f$, $\lfloor T_f/(2 \cdot T_p) \rfloor \cong T_f/(2 \cdot T_p)$. The expression of the average number of UCPs $\mathbb{E}[L^{\text{UNSL}}]$ involving two users follows equation (4) with \overline{N}_S instead of N_S

$$\mathbb{E}[L^{\text{UNSL}}] = \binom{N_u}{2} \cdot \Pr\{U_1 \odot U_2\} = \frac{\binom{N_u}{2}}{\binom{\overline{N}_S}{d}}. \quad (5)$$

3) *Unslotted Case with FEC*: We are considering two users interfering with each other with the same received signal-to-noise ratio Γ . Unless a certain level of interference is not exceeded, the replicas can be still decoded, since FEC is protecting the packets. This results in a reduction of the vulnerable period duration w.r.t. the case without FEC. Moreover, the level of interference sustainable for correctly decoding packets will depend on the rate R selected and on Γ .

Without loss of generality, we assume that the replica of interest has a first section free of interference and a second part interfered. Thus, the capacity computation can be split in two parts. In order to compute the minimum section that shall be interference-free for decoding correctly a packet, we equal the capacity of the replica to the rate R . We can then write

⁷For the slotted case we could have started our derivation from the same point as here. The vulnerable period is one transmission period T_p , in contrast with the unslotted case. Furthermore, each slot has the duration of one transmission period and since the MAC frame duration is T_f as in the unslotted case, we can conclude that $1/N_S = T_p/T_f$. In slotted schemes, it is more common to express all the quantities in terms of slot duration rather than explicitly define the transmission period and the frame duration.

$$\varphi \log_2(1 + \Gamma) + (1 - \varphi) \log_2(1 + \gamma_a) = R, \quad (6)$$

where $\gamma_a = \frac{\Gamma}{1+\Gamma}$. For simplicity, we call

$$\begin{aligned} r_f &= \log_2(1 + \Gamma) \\ r_i &= \log_2(1 + \gamma_a) \end{aligned}$$

and we solve equation (6) for φ

$$\varphi = \frac{R - r_i}{r_f - r_i}. \quad (7)$$

Equation (7) is valid for $R \geq \log_2(1 + \gamma_a)$. In fact, for $R < r_i$ no UCPs involving only two users can be observed. Regardless the level of interference, packets involved in collisions with only one other packet can be always decoded in this case. In order to extend equation (7) to all the admissible values of R we can write

$$\varphi = \begin{cases} \frac{R - r_i}{r_f - r_i} & \text{for } R \geq r_i \\ 0 & \text{for } R < r_i \end{cases}$$

It is worth noticing that φ is constrained to $0 \leq \varphi \leq 1$, since the selectable rate R is $R \leq \log_2(1 + \Gamma) = r_f$ for reliable communication.

The vulnerable period is reduced from $2 \cdot T_p$ to $2 \cdot T_p \cdot \varphi$. The expression of the average number of UCPs $\mathbb{E}[L^{\text{UNSL-FEC}}]$ involving two users follows equation (5), where we need to define $\hat{N}_S = \lfloor T_f / (2 \cdot T_p \cdot \varphi) \rfloor$ in place of \bar{N}_S

$$\mathbb{E}[L^{\text{UNSL-FEC}}] = \frac{\binom{N_u}{2}}{\binom{\hat{N}_S}{d}}. \quad (8)$$

4) *Unslotted Case for MRC with FEC and $d = 2$* : We start from the same assumptions as in the previous section, i.e. two users are interfering each other with the same Γ and we further assume that $d = 2$. Without loss of generality, we can assume that a first section of both replicas is free of interference, while there is a second part where just one replica is interfered and finally there is the last part where both replicas are interfered. As previously, we aim at computing the minimum packet portion interference free that is required for correctly decoding the replica,

therefore we equal the capacity to the rate R . We need also to take into account that MRC procedure sums the Γ of the replicas, therefore we can write

$$\varphi \log_2(1 + 2 \cdot \Gamma) + \mu \log_2(1 + \gamma_b) + (1 - \varphi - \mu) \log_2(1 + \gamma_c) = R.$$

where $\gamma_b = \Gamma + \gamma_a$ and $\gamma_c = 2 \cdot \gamma_a$. For simplicity we can call

$$r_f = \log_2(1 + 2 \cdot \Gamma)$$

$$r_{i1} = \log_2(1 + \gamma_b)$$

$$r_{i2} = \log_2(1 + \gamma_c),$$

and we can write

$$\varphi \cdot r_f + \mu \cdot r_{i1} + (1 - \varphi - \mu) \cdot r_{i2} = R. \quad (9)$$

In order to solve equation (9), we express μ as a function of φ , as $\mu = \alpha \cdot \varphi$, where $0 \leq \alpha \leq (1 - \varphi)/\varphi$. When $\alpha = 0$, there are no portions where only one out of the two replicas is interfered, while $\alpha = (1 - \varphi)/\varphi$ represents the case when there are no portions where both replicas are interfered. Resolving (9) for φ we find

$$\varphi = \frac{R - r_{i2}}{r_f - r_{i2} + \alpha \cdot (r_{i1} - r_{i2})}.$$

Also in this case, for $R < r_{i2}$, $\varphi = 0$ which means that no UCP involving two replicas can be found,

$$\varphi = \begin{cases} \frac{R - r_{i2}}{r_f - r_{i2} + \alpha \cdot (r_{i1} - r_{i2})} & \text{for } R \geq r_{i2} \\ 0 & \text{for } R < r_{i2} \end{cases}$$

The vulnerable period is $2 \cdot T_p \cdot \frac{\varphi + \alpha\varphi}{1 + \alpha}$, where the expression $\frac{\varphi + \alpha\varphi}{1 + \alpha}$ represents the average minimum collision length that prevents the correct decoding of MRC.

$$\mathbb{E}[L^{\text{UNSL-MRC}}] = \frac{\binom{N_u}{2}}{\binom{\tilde{N}_S}{d}}, \quad (10)$$

where $\tilde{N}_S = \lfloor T_f / (2 \cdot T_p \cdot \frac{\varphi + \alpha\varphi}{1 + \alpha}) \rfloor$.

B. Approximation of the PER

The packet error rate PER, denoted in the following as P_B , is expressed as

$$P_B = \frac{\mathbb{E}(E)}{N_u},$$

where $\mathbb{E}(E)$ is the expected number of users involved in an UCP. We conjecture that a good approximation of P_B in the low channel traffic region is given by

$$P_B \approx \frac{2 \cdot \mathbb{E}[L]}{N_u},$$

where $\mathbb{E}[L]$ is the average number of UCP involving two users and can be computed using equations (4), (5), (8) or (10), depending on the protocol used. In Section VI-A, we will show, via Monte Carlo simulations, that this approximation is particularly tight for low channel traffic conditions.

Useful relations are as follows. $\mathbb{E}(E)$ can be written as

$$\mathbb{E}(E) = \sum_{E=0}^{N_u} P_E(E) \cdot E = \sum_{E=0}^{N_u} \sum_{A \in \mathcal{A}} P_{E|A}(E|A) \cdot P_A(A) \cdot E, \quad (11)$$

where \mathcal{A} is the set of UCPs. We can write a lower bound of equation (11) as

$$\mathbb{E}(E) > \sum_{A \in \mathcal{A}} 2 \cdot P_{2|A}(2|A) \cdot P_A(A). \quad (12)$$

The lower bound identified in equation (12), can be upper bounded with the help of the computed average number of UCP in the previous sections as

$$\sum_{A \in \mathcal{A}} 2 \cdot P_{2|A}(2|A) \cdot P_A(A) < 2 \cdot \mathbb{E}[L].$$

VI. PERFORMANCE ANALYSIS

In the following, CRA and ECRA are compared in terms of two performance metrics, PER and throughput. The PER is the probability of erroneous packet decoding and includes both packet errors due to channel impairments and due to unresolvable collisions with other packets. The throughput is defined as the expected number of successfully decoded packets per transmission period T_p . Both PER and throughput for ECRA-SC and ECRA-MRC have been evaluated through Monte Carlo simulations. The throughput S is

$$S = (1 - P_B) \cdot G. \quad (13)$$

As soon as FEC is introduced, the throughput comparison between unslotted schemes (CRA, ECRA-SC and ECRA-MRC) and slotted ones as CRDSA is not able to capture completely their efficiency. In slotted protocols, if we assume that no power unbalance is present between the received packets and FEC cannot counteract any collision, packets are decoded only if they are received collision-free. Therefore, regardless of the selected coding rate R , the throughput performance remains the same⁸. In unslotted protocols instead, the packets involved in collisions can be decoded until a certain level of interference is not exceeded. The level of interference acceptable for allowing correct decoding depends on the rate R . On the other hand, lower rates decrease the useful information carried by the packets. For this reason, when FEC is used, a different metric has to be adopted

$$\xi = (1 - P_B) \cdot G \cdot R, \quad (14)$$

where ξ represents the spectral efficiency expressed in information bits/s/Hz of the MAC scheme.

Although both CRA and ECRA can outperform considerably the ALOHA protocol (and also SA) they require on average more power. In fact, these schemes assume to replicate each packet sent in the frame d times. In order to consider this effect, we follow the approach of [5], that was extended for CRDSA and IRSA in [16], and based on it we can investigate the *normalized capacity* of the CRA and ECRA schemes.

The idea is to compute the capacity of one of the unslotted MAC schemes (CRA, ECRA-SC or ECRA-MRC) and normalize it to the sum rate capacity of the multiple access Gaussian channel $C_{ref} = \log_2(1 + P_{ag}/N)$. This is done fixing the average aggregate received signal power P_{ag} equal in all the schemes. We would like to compute the ultimate performance of the unslotted RA schemes and therefore we define the maximum capacity C_{max} as

$$C_{max} = \max_{R \in [0, \dots, R_M]} S(G) \cdot R,$$

⁸Assuming the Shannon's capacity limit, this is true unless $\log_2\left(\frac{2\Gamma+1}{\Gamma+1}\right) < R \leq \log_2(1 + \Gamma)$.

where for each channel traffic value, the rate R which maximizes the spectral efficiency is chosen. It has to be noted that, the user transmission power P_u takes into account the fact that the channel is used intermittently, i.e. $P_u = \frac{P_{ag}}{G \cdot d}$. Moreover, the throughput expression $S(G)$ is not available in closed form for CRA, ECRA-SC and ECRA-MRC. Finally, the limit on the rate R_M is $R_M = \log_2(1 + P_u/N)$ and depends upon the selected channel load G . Now, we can define the maximum normalized capacity η_{max} as

$$\eta_{max} = \frac{C_{max}}{C_{ref}}, \quad (15)$$

where, depending on the RA, a different expression of C_{max} will be used in equation (15). In fact, the throughput $S(G)$ will depend on the RA protocol considered.

A. Numerical Results

In the following, numerical results for ECRA-SC and ECRA-MRC schemes are presented. Ideal interference cancellation is assumed and the threshold collision model of Section III-B is used for determining the successful decoding of a packet.

In the set of simulations, the symbol duration T_s and the frame duration T_f are assumed to be $T_s = 1 \mu s$ and $T_f = 100 \text{ ms}$ respectively. The packets sent by the N_u users are composed by $L_b = 1000$ bits, which translate in $L_s = L_b/R$ symbols. The transmission period is then $T_p = T_s \cdot L_s$. Furthermore, we recall that the number of users generating traffic is $N_u = G \cdot (T_f/T_p)$ and each of the users generates $d = 2$ replicas.

We present first the simulations of the throughput and PER for both ECRA-SC and ECRA-MRC. For reference purposes also CRA and the ALOHA protocols are depicted in the figures. The assumptions are, received SNR $\Gamma = 6 \text{ dB}$ equal for all users and code rate $R = 1.5$.

In Fig. 4 the throughput S vs. the offered channel traffic G is presented. ECRA-MRC largely outperforms both ECRA-SC and CRA, reaching a maximum throughput of $S^{\text{MRC}} = 1.18$ at $G = 1.2$, which is more than twice the one of CRA, $S^{\text{CRA}} = 0.56$ and 71% of increase with respect to the one of ECRA-SC, $S^{\text{SC}} = 0.69$. Furthermore, ECRA-MRC throughput follows linearly the offered channel traffic up to more than one packet per T_p duration, implying very limited PER. In fact, looking at the PER performance in Fig. 5, ECRA-MRC is able to maintain the PER below 10^{-3} for offered channel traffic below one packet per T_p duration.

In this way, ECRA-MRC can guarantee $P_B \leq 10^{-3}$ under the presented simulation conditions up to $G = 1$, while both ECRA-SC and CRA can be operated only up to $G \cong 0.1$ for the same

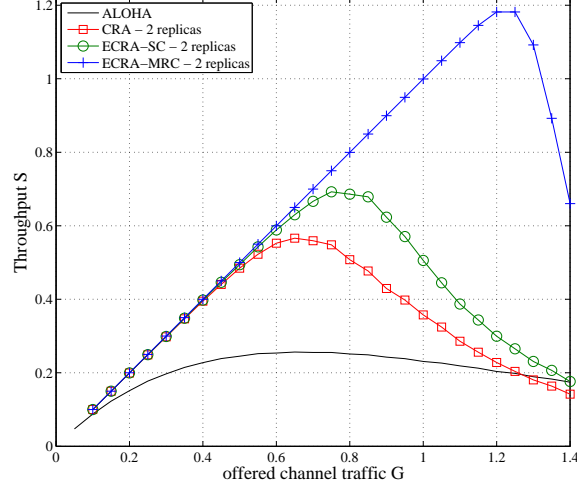


Fig. 4. Throughput S vs. offered channel traffic G for ALOHA, CRA, ECRA-SC and ECRA-MRC, $\Gamma = 6$ dB and $R = 1.5$.

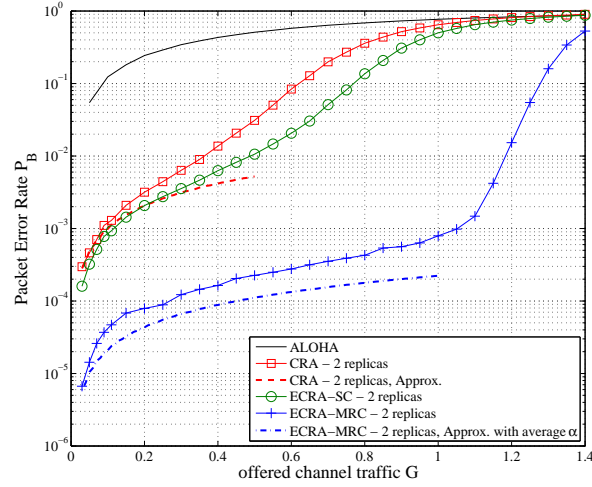


Fig. 5. Packet error rate P_B vs. offered channel traffic G for ALOHA, CRA, ECRA-SC and ECRA-MRC, $\Gamma = 6$ dB and $R = 1.5$. The average value of α used in the approximation of P_B for ECRA-MRC is derived through Monte Carlo simulations.

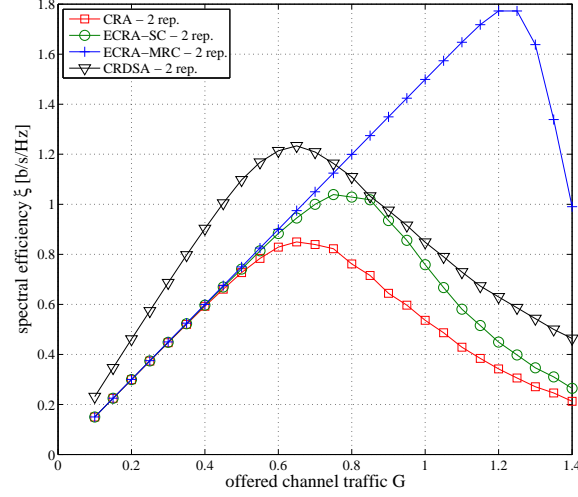
PER. The gain of ECRA-MRC with respect to both ECRA-SC and CRA in terms of PER is of at least one order of magnitude, except in the very high channel traffic region. It is also shown in the figure, that this protocol is the only one that can reach $P_B \leq 10^{-4}$. Very low PER are particularly appealing in specific scenarios as satellite applications or control channels where reliability can be as important as efficiency.

In Fig. 5, the approximation on the P_B for both CRA and ECRA-MRC, derived in Section V-B,

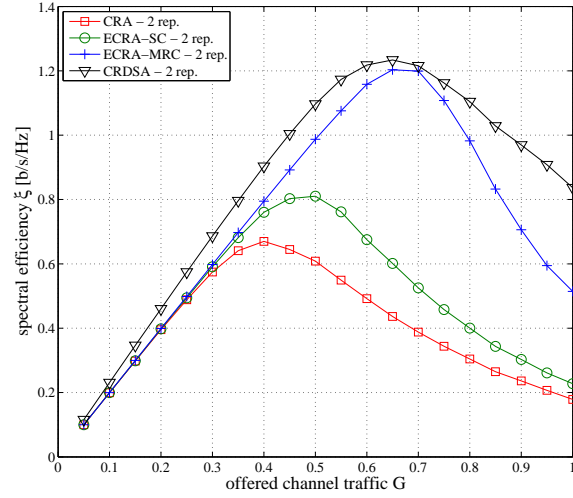
is also shown. This approximation takes into account only the errors coming from UCPs involving two users, and for very limited offered channel traffic values is very close to the simulated P_B . For CRA, when $G \leq 0.2$, the approximation approaches the P_B simulated performance, while for increasing G the probability of having UCPs involving more than two users starts to have an impact on P_B and therefore the approximation starts to become loose. Since the performance of CRA and ECRA-SC are similar, especially for limited G , the approximation for CRA can be exploited also for ECRA-SC. Although a similar behavior can be found for the approximation of ECRA-MRC, interestingly the relative distance between the approximation and the simulations remains almost constant for a large range of offered traffic values. Both approximations (the one of CRA and the one of ECRA-MRC) can be used for predicting the PER performance limits of the protocols under very limited offered channel traffic that are particularly relevant for many applications e.g., satellite applications.

In the second set of simulations, performance comparison of the slotted scheme CRDSA with the unslotted schemes CRA, ECRA-SC and ECRA-MRC is presented. The metric used for the comparison is the spectral efficiency ξ . We recall for the sake of completeness that CRDSA has the same throughput $S(G)$ performance for $\log_2\left(\frac{2\Gamma+1}{\Gamma+1}\right) < R \leq \log_2(1+\Gamma)$, under the assumption of equal received power for all users and no multi-packet reception. Therefore, we have selected for both the simulations $R^{\text{CRDSA}} = \log_2(1+\Gamma)$. For the unslotted schemes (CRA, ECRA-SC and ECRA-MRC) we selected the rate R^{UNSL} with $R^{\text{UNSL}} < \log_2(1+\Gamma)$ (and therefore $R^{\text{UNSL}} < R^{\text{CRDSA}}$) and equal for all the schemes.

In Fig. 6 the aforementioned comparison is presented for a fixed received SNR, $\Gamma = 6$ dB. In the first scenario, Fig. 6(a), the rate for the unslotted schemes is $R^{\text{UNSL}} = 1.5$ while in the second one, Fig. 6(b), is $R^{\text{UNSL}} = 2$. In the case of $R^{\text{UNSL}} = 1.5$, two regions can be identified depending on the channel traffic G . In the first region delimited by channel traffic values $0 < G \leq 0.75$, the slotted scheme CRDSA is outperforming all the unslotted ones, reaching its maximum around 1.2 b/s/Hz, for $G = 0.65$. Under low packet error rates, the coding rate R is dominating the spectral efficiency performance. For this reason, CRDSA has a greater positive slope than the unslotted schemes for limited offered channel traffic. In the second region $0.75 < G \leq 1.4$ instead, while CRDSA starts degrading its spectral efficiency performance due to the increasing number of unresolvable collisions, ECRA-MRC spectral efficiency starts exceeding the one of CRDSA. In this specific scenario, ECRA-MRC is able to support channel traffic above $G = 1$. Both ECRA-SC and CRA have worse performance than ECRA-MRC reaching a maximum



(a) $\Gamma = 6$ dB and for the unslotted schemes $R^{\text{UNSL}} = 1.5$.



(b) $\Gamma = 6$ dB and for the unslotted schemes $R^{\text{UNSL}} = 2$.

Fig. 6. Spectral efficiency ξ vs. offered channel traffic G for CRDSA, CRA, ECRA-SC and ECRA-MRC.

spectral efficiency of 59% and 48% of the one of ECRA-MRC, respectively.

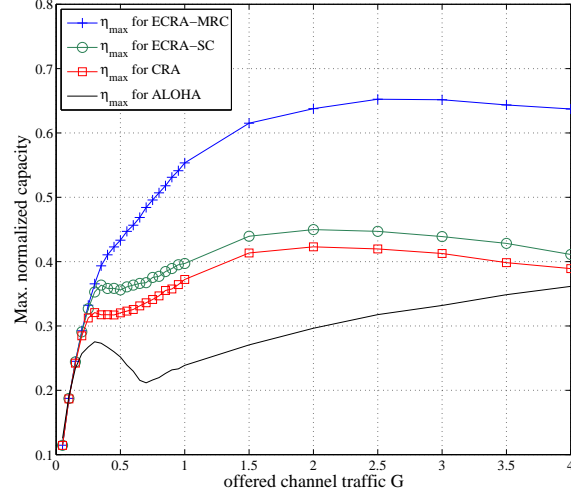
In the second scenario where $R^{\text{UNSL}} = 2$ and shown in Fig. 6(b) the behavior is different. The unslotted schemes under a higher coding rate show worse performance. It can be noted, that for CRDSA the same rate was selected since the received SNR is the same in the two scenarios. In this case, ECRA-MRC has similar but always slightly worse performance than CRDSA. The increase of coding rate, although beneficial under low channel traffic conditions, degrades the SIC performance under moderate and high traffic conditions limiting the overall performance for

the unslotted schemes. Interestingly enough, unslotted schemes are very sensitive to the selection of the coding rate R , as the results have shown. In this sense, a careful selection of the coding rate based on the expected received SNR has to be carried out in order to exploit as much as possible the benefit of schemes like ECRA-MRC.

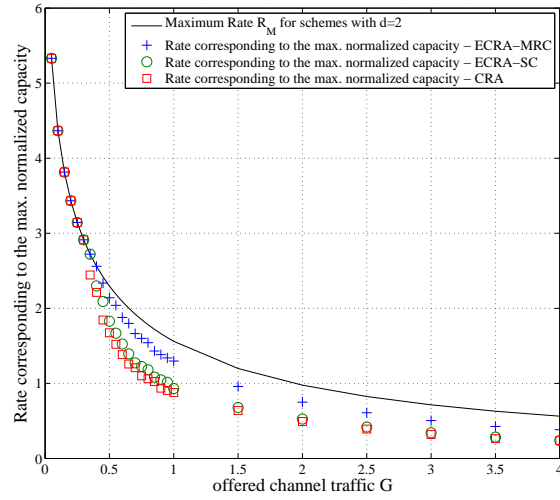
The last set of simulations shows the comparison among ALOHA, CRA, ECRA-SC and ECRA-MRC, of the maximum normalized capacity η_{max} and the results are presented in Fig. 7(a). The scenario under consideration is with $P_{ag}/N = 6$ dB for all the schemes.

We can observe that in this scenario, the maximum normalized capacity for ECRA-MRC can reach up to 65% of the MAC channel capacity, for a channel traffic $G = 2.5$ with rate $R \cong 0.6$; see Fig. 7(b). At this channel load, the gain is 46% with respect to ECRA-SC and 56% with respect to CRA. Interestingly, the maximum normalized capacity for ECRA-MRC as well as for both ECRA-SC and CRA is relatively constant for heavy channel traffic i.e., $G > 2$. In this way, the schemes appear to be robust against channel traffic fluctuations. On the other hand, the maximum normalized capacity is found for different rates as the channel traffic changes; see Fig. 7(b). Therefore the system is required to adapt the rate in order to reach the best performance in terms of normalized capacity. Nevertheless, the adaptation of the rate remains quite limited in this channel traffic region, ranging from a maximum of 0.75 at $G = 2$ to a minimum of 0.38 at $G = 4$ for ECRA-MRC. For limited channel traffic, all the schemes performs very close, with ALOHA being slightly the best option. Under this traffic conditions in fact, the collisions are very seldom and do not limit the PER. In this way, since ALOHA do not uses replicas, has more power available for each transmitted packet and can therefore use a greater rate.

In Fig. 7(b), the rate corresponding to the maximum normalized capacity for ECRA-MRC, ECRA-SC and CRA is shown compared with the maximum rate possible under this scenario, depicted with a solid line. For low channel traffic, the outer bound on the normalized capacity is achieved when the rate coincides with the maximum rate allowed, supporting the fact that collisions of received packets are here seldom and the normalized capacity can be maximized increasing the rate as much as it is allowed. On the other hand, as soon as the channel traffic exceeds $G = 0.4$, the outer bound of the normalized capacity is found for rates below the maximum one. In this way, the normalized capacity under moderate to high channel traffic conditions can be maximized taking a margin with respect to the maximum rate. This margin is helpful to counteract part of the collisions and at the same time does not reduces heavily the spectral efficiency. As a final remark, for ALOHA, CRA and ECRA-SC when the rate maximizing



(a) Maximum normalized capacity η_{max} for ALOHA, CRA, ECRA-SC and ECRA-MRC with $P_{ag}/N = 6$ dB.



(b) Rate maximising the normalized capacity for CRA, ECRA-SC and ECRA-MRC with $P_{ag}/N = 6$ dB.

Fig. 7. Maximum normalized capacity η_{max} for ALOHA, CRA, ECRA-SC and ECRA-MRC with $P_{ag}/N = 6$ dB and corresponding rate.

the normalized capacity moves away from the maximum rate, the maximum normalized capacity experiences a local maximum, followed by a local minimum. For example, looking at the ECRA-SC curves of the maximum normalized capacity, we can observe that a local maximum is found for $G = 0.35$, which corresponds to the last rate on the maximum allowed in Fig. 7(b), after this point the upper bound changes slope, and the rate of the maximum normalized capacity drifts away from the maximum rate⁹.

VII. CONCLUSIONS

In this paper, a novel RA decoding algorithm named ECRA has been presented. Motivated by the presence of UCPs within frames, ECRA tries to reduce their detrimental impact on the receiver's SIC procedure applying combining techniques. Following the approach of CRA, ECRA exploits the presence of multiple instances of the same packet in order to trigger a SIC procedure. In addition, ECRA tries to reduce interference of unslotted protocols attempting to resolve partial collisions among packets, with the creation of combined packets. Combined packets can be either generated from the lowest interfered parts of the replicas sent within the frame, i.e. SC, or from the weighted combination of the replicas symbols of each user, i.e. MRC. An analytical framework for evaluating a lower bound on the UCP for CRDSA, CRA with and without FEC as well as ECRA is developed. The lower bound is then used for computing an approximation of the PER which is found to be tight in the low channel traffic regime.

A comprehensive framework with different metrics is also derived, in order to compare both unslotted and slotted schemes with FEC. Finally, an investigation on the performance of ECRA under average power constraint is performed.

Numerical simulations have shown that ECRA in both its variants, largely outperforms CRA in all the considered scenarios for both throughput and PER. The simulations have shown that ECRA-MRC is able to double the maximum throughput w.r.t. CRA. ECRA-SC instead, has an improvement of 23% in the maximum throughput w.r.t. CRA. For a specific rate, ECRA-MRC is also able to outperform CRDSA with the same number of replicas for a specific rate scenario, while in a second rate scenario it is able to show similar performance. Finally, ECRA-MRC shows remarkable performance in terms of normalized capacity reaching up to 65% the MAC channel capacity.

⁹Please note that the rate for ALOHA is not depicted in Fig. 7(b) because it has a different degree d , and therefore the results are hardly comparable.

REFERENCES

- [1] N. Abramson, "Multiple Access in Wireless Digital Networks," *Proceedings of IEEE*, vol. 82, No. 9, pp. 1360–1370, 1994.
- [2] C. Kissling, "Performance Enhancements for Asynchronous Random Access Protocols over Satellite," in *Proc. IEEE Intl. Conf. Comm. (ICC)*, Kyoto, Japan, June 2011, pp. 1–6.
- [3] N. Abramson, "The ALOHA system: Another alternative for computer communications," in *Proc. of the 1970 Fall Joint Comput. Conf., AFIPS Conf.*, vol. 37, Montvale, N. J., 1970, pp. 281–285.
- [4] L. G. Roberts, "ALOHA packet system with and without slots and capture," *Proc. SIGCOMM Comput. Commun. Rev.*, vol. 5, pp. 28–42, April 1975.
- [5] N. Abramson, "The Throughput of Packet Broadcasting Channels," *IEEE Trans. Comm.*, vol. 25, no. 1, pp. 117–128, January 1977.
- [6] D. Pompili and I. Akyildiz, "Overview of Networking Protocols for Underwater Wireless Communications," *IEEE Comm. Magazine*, vol. 47, pp. 97–102, 2009.
- [7] Y. He and X. Wang, "An ALOHA-Based Improved Anti-Collision Algorithm for RFID Systems," *IEEE Wireless Comm.*, vol. 20, No. 5, pp. 152–158, October 2013.
- [8] H. Menouar, F. Filali, and M. Lenardi, "A Survey and Qualitative Analysis of MAC Protocols for Vehicular Ad Hoc Networks," *IEEE Wireless Comm.*, vol. 13, pp. 30–35, 2006.
- [9] C. Stefanovic and P. Popovski, "ALOHA Random Access that Operates as a Rateless Code," *IEEE Trans. Comm.*, vol. 61, No. 11, pp. 4653–4662, November 2013.
- [10] H. Peyravi, "Medium Access Control Protocols Performance in Satellite Communications," *IEEE Comm. Magazine*, vol. 37, pp. 62–71, 1999.
- [11] E. Casini, R. De Gaudenzi, and O. del Rio Herrero, "Contention Resolution Diversity Slotted ALOHA (CRDSA): An Enhanced Random Access Scheme for Satellite Access Packet Networks," *IEEE Trans. Wireless Comm.*, vol. 6, no. 4, pp. 1408–1419, April 2007.
- [12] G. Choudhury and S. Rappaport, "Diversity ALOHA - A Random Access Scheme for Satellite Communications," *IEEE Trans. Comm.*, vol. 31, no. 3, pp. 450 – 457, March 1983.
- [13] L. Kleinrock, *Queueing Systems - Volume II: Computer Applications*, J. W. . Sons, Ed. Wiley Interscience, 1976.
- [14] O. del Rio Herrero and R. de Gaudenzi, "Generalized Analytical Framework for the Performance Assessment of Slotted Random Access Protocols," *IEEE Trans. Wireless Comm.*, vol. 13, pp. 809–821, 2014.
- [15] C. Kissling, "On the stability of Contention Resolution Diversity Slotted ALOHA (CRDSA)," in *Proc. IEEE Global Comm. Conf. (GLOBECOM)*, Houston, TX, USA, December 2011, pp. 1–6.
- [16] G. Liva, "Graph-Based Analysis and Optimization of Contention Resolution Diversity Slotted ALOHA," *IEEE Trans. Comm.*, vol. 59, no. 2, pp. 477–487, February 2011.
- [17] E. Paolini, G. Liva, and M. Chiani, "Coded Slotted ALOHA: A Graph-Based Method for Uncoordinated Multiple Access," *Submitted to IEEE Trans. Inf. Theory*.
- [18] K. R. Narayanan and H. D. Pfister, "Iterative Collision Resolution for Slotted ALOHA: An Optimal Uncoordinated Transmission Policy," in *Proc. 7th Intl. Symp. on Turbo Codes and Iterative Information Processing (ISTC)*, 2012.
- [19] C. Stefanovic, P. Popovski, and D. Vukobratovic, "Frameless ALOHA Protocol for Wireless Networks," *IEEE Comm. Letters*, vol. 16, pp. 2087–2090, 2012.
- [20] S. Gollakota and D. Katabi, "ZigZag Decoding: Combating Hidden Terminals in Wireless Networks," in *Proc. Intl. Conf. of Special Interest Group on Data Comm. (SIGCOMM)*, 2008, pp. 159–170.

- [21] A. S. Tehrani, A. G. Dimakis, and M. J. Neely, "SigSag: Iterative Detection through Soft Message-Passing," in *Proc. IEEE Intl. Conf. on Computer Comm. (INFOCOM)*, 2011.
- [22] R. De Gaudenzi, O. del Rio Herrero, G. Acar, and E. G. Barrabes, "Asynchronous Contention Resolution Diversity ALOHA: Making CRDSA Truly Asynchronous," *IEEE Trans. Wireless Comm.*, vol. 13, no. 11, pp. 6193–6206, Nov. 2014.
- [23] D. G. Brennan, "Linear Diversity Combining Techniques," *Proc. IRE*, 1959.
- [24] W. C. Jakes, *Microwave Mobile Communication*. Wiley-IEEE Press, 1974.
- [25] A. Meloni, M. Murrioni, C. Kissling, and M. Berio, "Sliding Window-Based Contention Resolution Diversity Slotted ALOHA," in *Proc. IEEE Global Comm. Conf. (GLOBECOM)*, 2012.
- [26] L. Tong, Q. Zhao, and G. Mergen, "Multipacket Reception in Random Access Wireless Networks: From Signal Processing to Optimal Medium Access Control," *IEEE Comm. Magazine*, pp. 108–112, November 2001.
- [27] S. Ghez, S. Verdu, and S. C. Schwartz, "Stability Properties of Slotted Aloha with Multipacket Reception Capability," *IEEE Trans. Automatic Control*, vol. 33, no. 7, pp. 640–649, July 1988.
- [28] M. Zorzi and R. R. Rao, "Capture and Retransmission Control in Mobile Radio," *IEEE J. Select. Areas in Comm.*, vol. 12, no. 8, pp. 1289–1298, October 1994.
- [29] C. Kissling and F. Clazzer, "LDPC Code Performance and Optimum Code Rate for Contention Resolution Diversity ALOHA," in *Proc. IEEE Global Comm. Conf. (GLOBECOM)*, Atlanta, GA, USA, December 2013, pp. 2954–2960.
- [30] F. Clazzer and C. Kissling, "Optimum Header Positioning in Successive Interference Cancellation (SIC) based ALOHA," in *Proc. IEEE Intl. Conf. on Comm. (ICC)*, Budapest, Hungary, June 2013, pp. 2869–2874.